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TECHNICAL MEMORANDUMS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

No. 329

ATOMIZATION OF LIQUID FUELS.

By Dr. Kuehn.

PART I.

RELATION BETWEEN ATOMIZATION AND COMBUSTION.

METHODS EMPLOYED FOR DETERMINING THE SIZE OF
PARTICLES AND SMALL DROPS.

CHOICE OF EXPERIMENTAL METHOD.

From "Der Motorwagen," July 10 and 20, 1924.

Washington,
September, 1925.



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ATOMIZATION OF LIQUID FUELS.*

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PART I.

Introduction.

Relation between Atomization and Combustion.

Both theory and practice demand the finest possible atomization of liquid fuels for direct injection into the cylinders of internal combustion engines. This requirement is based on the subsequent process of combustion, which can take place successfully and economically only under certain definite conditions. Injection and combustion are therefore very intimately related, the former serving as a preparation for the latter, in that it must provide the preliminary conditions for the kind of combustion desired. The combustion process accordingly determines the conditions of injection and atomization.

* From "Der Motorwagen," July 10 and 20, 1924.

The explanation of the combustion process has been so often attempted in other places, that it is not necessary to take it up now in detail.* Moreover, the combustion process is of interest to us here, only in so far as it has to do with the preliminary atomization. If there is in the combustion chamber a mixture of fuel and air in a definite ratio and at a pressure and temperature known to be favorable for the combustion, greatly varying combustion phenomena could still be obtained, according to the nature of the mixture. We wish to obtain the most complete, uniform and rapid combustion possible. It is obvious that this object will be more fully attained, the more thoroughly and uniformly the fuel is previously mixed with the air. On the one hand, the fuel must be divided into the smallest possible particles and, on the other hand, these particles must be distributed as uniformly as possible throughout the combustion chamber, in order that each fuel molecule may be in immediate contact with the oxygen molecules required for its combustion.

Due to the varying characteristics of the liquid fuels now available, the desired mixture with the combustion air can be obtained only by employing different methods and even then only incompletely with many fuels. The most volatile fuels offer the

* See Alt, "Flüssige Brennstoffe und ihre Verbrennung in der Dieselmachine," Zeitschrift des Vereines deutscher Ingenieure, 1923, p.686 (N.A.C.A. Technical Memorandum No. 281). Von Wartenberg, "Verbrennungsvorgänge in Dieselmotoren," a lecture before the "Westpreuss. Bezirksverein des V.d.I.," Nov. 8, 1921. Wollers and Ehmke, "Der Vergasungsvorgang der Treibmittel," Kruppsche Monatshefte, Jan., 1921. Moore, "The Spontaneous Ignition Temperatures of Liquid Fuel," a lecture before the "Institution of Petroleum Technologists," Jan., 1920, Engineering, 1920, p.151.

least difficulty, since they can be previously mixed with air outside the combustion chamber. More difficulty is experienced with fuels which evaporate only slightly or not all at atmospheric pressure and temperature. These can only be evaporated by heating, after being mechanically divided and mixed with the combustion air. Any preliminary heating, which would appear to be the simplest method for more finely dividing the already mechanically sprayed fuel, is attended, however, by serious disadvantages. It is obvious that the air surrounding the particles of fuel must have the same temperature as the latter. If the cylinder walls do not have the same temperature, condensation immediately occurs. The drops of fuel thus precipitated burn with great difficulty and cause the undesirable after-burning and the deposit of carbon in the cylinder. Moreover, any considerable heating of the combustion air outside the cylinder lowers the volumetric efficiency of the engine and causes premature ignitions and knocking. Lastly, it must be remembered that the process of evaporation requires a certain length of time, according to the density of the fuel. This time requirement is very difficult to bring into harmony with the functioning conditions of the engine. In the questions under consideration, the time plays an exceedingly important role, since both the mixing and the combustion processes require a certain amount of time.* In

* Hawkes, "Fuel Oil in Diesel Engines," a lecture before the North East Coast Institution of Engineers and Shipbuilders, Nov. 26, 1920, pp. 749 and 786. Gunther, "Kompressorlose Dieselmotoren," Der Motorwagen, 1923, pp. 387 and 423.

the cylinder of an internal combustion engine, there is available for these processes only a very short space of time, which we are trying to shorten still further, in order to attain greater piston and revolution speeds. Hence the mixing and combustion must be accelerated as much as possible. These processes will be more rapid and complete, however, the more thoroughly the fuel is atomized at the beginning.

The injection of the fuel by means of compressed air has thus far proved to be the best way to obtain the desired degree of atomization. This method, however, requires a complex compressor plant. Moreover, the introduction of cold compressed air into the combustion chamber has disadvantageous effects on the functioning of the engine, so that the attempt has recently been made to dispense with the compressed air. In particular, an attempt is being made to attain the requisite degree of atomization by the direct injection of the liquid fuel through a suitable nozzle by means of pressure alone, without the aid of compressed air.*

* Hesselman, "Hochdruckmotor mit Einspritzung des Brennstoffes ohne Druckluft," Z.d.V.d.I., 1923, p.658 (N.A.C.A. T.M. No. 312). Neumann, "Untersuchungen an der Dieselmachine," Z.d.V.d.I., 1923, p.755. Hawkes, "Some Experimental Work in Connection with Diesel Engines," a lecture before the "Institution of Naval Architects," July 8, 1920, Engineering, 1920, p.127. Hawkes, "Injection and Combustion of Fuel Oil," Motorship (New York), 1921, Feb., April, June, July, August. Chaloner, "Air Injection or Mechanical Injection," Motorship, 1921, Feb., April. Nagel, "Die Dieselmachine der Gegenwart," Z.d.V.d.I., 1923, pp.677, 711, 725, 778, 808.

In the present treatise, we will consider chiefly the problem of solid injection in comparison with air injection. On leaving the valve or nozzle through one or more small openings, the fuel is split up into innumerable fine drops, which penetrate the combustion chamber in divergent directions in the form of a conical jet. The efficiency of this jet is judged from the following three viewpoints:

1. With respect to the fineness of the atomization. The individual drops must be as small as possible and not differ too much from one another in size. Large drops, even when isolated in a finely atomized cone, have a detrimental effect on the combustion.

2. With respect to the direction or distribution of the sprayed particles. The jet must have such a shape and direction as to render it possible for the particles to penetrate every part of the combustion chamber.

3. With respect to the penetration of the particles. At least the larger particles in the jet must have sufficient mass and velocity to enable them to penetrate the farthest part of the combustion chamber before burning.

Under certain conditions, the third requirement may work in opposition to the first, namely, when the atomization is so fine that the liquid particles immediately lose their initial velocity, through the resistance of the air, and burn near the nozzle. Then the fuel mixture is too rich near the nozzle and too poor

in the more remote portions of the combustion chamber. In this extreme case and likewise when the second requirement is not met, it has been attempted, through a suitable shape of the piston head and the cylinder walls, to produce violent eddies which shall distribute the fuel vapor to all parts of the combustion chamber before the beginning of the combustion.

Hitherto, our efforts have been chiefly confined to attaining the above objects by experimentation. The most ingenious and widely differing fuel valves, nozzles and spraying devices have been constructed and large sums have been continuously spent by firms interested in this problem, for the purpose of testing and improving these devices. Unfortunately, the results of these tests are mostly kept secret. Our endeavors have, however, resulted in giving us a fairly clear idea of the requirements for obtaining a good atomization and thereby improving the combustion and thus increasing the efficiency of internal combustion engines.

On the contrary, the real nature of atomization, its causes and the degree of fineness actually attained has thus far been scarcely touched. Hardly any data have been published on the size of the particles to be regarded as the criterion of the essential fineness of the atomization. There have been published only a few data on the size of the liquid particles and these are often contradictory and for the most part inapplicable to the atomization of fuel. Aside from the importance of the phys-

ical process of atomization, a knowledge of the size of the particles is important to the chemist in the study of the process of combustion. My incentive to this work came first from Prof. Wartenberg, who influenced me to take this step toward solving the problem of atomization.

Methods Employed for Determining the Size of Particles and Small Drops.

Any investigation of the drops produced by atomization necessitates the measurement of exceedingly small magnitudes. In order to obtain an idea of the orders of magnitude entering into such measurements, as likewise of the methods of measuring, a few extracts will first be given from articles on experiments with drops, solid particles, suspended particles, etc., of especial importance to engineers, who seldom find time to devote to this purely physical realm.

In an article on rain, Lenard gives information on the measurement of water drops.* Single drops were made to float in an ascending air current and thereby their falling speed determined. Then the drops were caught on blotting-paper and their size determined. The final velocity of the smallest drop was computed

* Lenard, "Ueber Regen," Meteorol. Zeitschrift, 1904, p. 249.

according to the formula of Stokes.* Accordingly the force K , which moves a drop, experiences, from the surrounding medium, a resistance of

$$W = 6 \pi [\eta] r c = K$$

wherein $[\eta]$ denotes a frictional constant of the medium in $\text{cm}^{-1} \text{g sec}^{-1}$ measured according to the absolute mass system; r , the radius of the drop; c , the final velocity. The constant final velocity of the smallest drops is therefore so small that the relative flow of the surrounding medium is laminar. Vortex movements do not come under consideration here. The resistance is due to the viscosity of the medium and is proportional to the first power of the velocity. The force K , is the resulting force of gravity $= m g$, wherein m denotes the mass of a spherical drop, of the volume $\frac{4}{3} \pi r^3$ and the density s , and g the acceleration due to gravity.

$$m g = \frac{3}{4} \pi r^3 s g = 6 \pi [\eta] r c$$

hence,

$$c = \frac{2}{9} \frac{g r^2 s}{[\eta]}$$

On the other hand, the final velocity of larger drops is already so great that vortex movements occur in the surrounding

* So long as their mass is of that order of magnitude, in which the falling motion is not affected by the impulse of the Brown movement. Concerning the applicability of the Stokes formula: see Horace Lamb, Textbook of Hydrodynamics; John Zeleny and L. W. McKeehan, "Die Endgeschwindigkeit des Falles kleiner Kugeln in Luft," Physikal Zeitschrift, 1910, p.78; Jean Perrin, "Die Brownsche Bewegung und die wahre Existenz der Molekule, Ann. Chim. et der Phys. 8, Serie, Sept. 18, 1909.

medium and hence its density is decisive, instead of the viscosity constant. The resistance then increases in proportion to the square of the velocity and to the first power of the cross-section of the drop and the density of the surrounding medium.

$$W = \pi r^2 c^2 s_1 A' = K = m g$$

wherein A' is an unnamed constant to be determined empirically as s_1 is the density of the surrounding medium. With $A' = \frac{3}{4} A$, we have

$$m g = \frac{4}{3} \pi r^3 s g = \frac{4}{3} \pi r^2 \cdot c^2 s_1 A$$

hence,

$$c = \sqrt{\frac{r g s}{A s_1}}$$

For the constant A , Lenard gives the value 0.153 obtained from experiments with falling water drops of 2-3 mm radius.* It is smaller than for solid spheres, which was found by Newton to be 0.376; by Borda, 0.225; by Hutton, 0.188. This leads us to conclude that drops have a tendency, in falling, to exchange their spherical shape for one of less resistance. The limit between the laminar and turbulent motion is formed by drops having a diameter of about 0.29 mm.

Since, as subsequent experimental results will show, we are only interested in drops of less than 2 mm diameter, only Stokes' formula comes into question for the determination of the constant final velocity in our experiments. For the viscosity constant of the air, Lenard gives the value $[\eta] = 0.000172 \frac{\text{g}}{\text{cm sec}}$ at 0°C ,

* Lenard, "Schwingungen fallender Tropfen," Wied. Ann. 1887, p. 230.

which is independent of the atmospheric pressure and increases with the temperature.* The final falling velocity of water drops in air is accordingly $c = 1270000 r^2$ or $c = 317500 d^2$ and is given in the following table in m/sec. for drops having a diameter of 0.01-0.2 mm.

d(mm)	c(m/sec.)	d(mm)	c(m/sec.)
0.01	0.0032	0.11	0.384
0.02	0.013	0.12	0.458
0.03	0.028	0.13	0.537
0.04	0.051	0.14	0.623
0.05	0.080	0.15	0.715
0.06	0.114	0.16	0.81
0.07	0.156	0.17	0.92
0.08	0.203	0.18	1.03
0.09	0.257	0.19	1.15
0.10	0.318	0.20	1.27

We see therefore that the falling velocity differs greatly, according to the size of the drops. Somewhat smaller values than those in the table were calculated by Liznar, who found more accu-

* Kirchhoff, "Vorlesungen über Mechanik," 1883, p.374. According to Wahrburg ("Lehrbuch der Physik") $[\eta] = 0.00018$. In "Die Unterkühlung beim Ausfluss gesättigten Dampfes" (Z.d.V.I., 1913), Stodola reckons with the value $[\eta] = 1.69 \times 10^{-6}$ (in $\frac{\text{kg sec.}}{\text{m}^2}$ according to the technical mass system) at 0°C . Accordingly $[\eta] = \eta g = 0.000166 \frac{\text{g}}{\text{cm sec.}}$. According to Millikan, "Ladung eines Ions und Stokessches Gesetz" (Phys. Zeitschrift XI, 1910) the viscosity of the air at 25.2°C is $[\eta] = 0.0001837$, a later figure chosen by him, as the mean value, being $[\eta] = 0.0001785$. Chwolson, "Lehrbuch der Physik," gives, for air, $[\eta] = 0.000175$ and according to Fabry and Perot, $[\eta] = 0.000173$. De Broglie, "Untersuchungen über die gasförmigen Suspensionen" (Phys. Zeitschrift, 1910, p.33) reckons with $[\eta] = 0.00018$ to 0.0002 .

accurate values covering the whole range from the smallest to the largest rain-drops, from formulas corrected according to experimental results. According to Liznar, very small drops with a radius of less than 0.05 mm have a falling velocity of $c = 873190 r^2$ (Liznar, "Die Fallgeschwindigkeit der Regentropfen," Meteorol. Zeitschr. 1914, p.339).

The mean diameters of the drops investigated by Lenard ranged from 1.28 to 6.36 mm. On these drops Lenard observed deformations and, in fact, flattenings in the vertical direction. Lenard had already described these deformations in a previously published treatise on the oscillations of falling drops (Lenard, "Ueber die Schwingungen fallender Tropfen," Wied. Ann. XXX, 1887) and reported that observations and photographs revealed no deformation of drops falling from a height of 3 m, but that, on the contrary, during a rain-storm by night, rain-drops, which were projected by electric sparks on a dull screen, showed flattenings pointed at the bottom. Since the deformations occur only after a fall of over 3 m and hence require time, Lenard explains their production through the tangential friction of the air which tends to carry the outer surface of the drop with it and thereby gradually gives the whole drop a whirling motion. The deformations increase the air resistance, thereby decreasing the falling velocity. This has been confirmed by corresponding experiments. Consequently, in the case of drops falling from a great height, the value given for the constant A is only applicable to drops

which are so small that their surface tension constantly protects them from noticeable deformation through inner vortices. As the upper limit of the diameter of the water drop, Lenard gives, for this case, a value of 0.5 mm, while Liznar computes it at 2.6 mm. For the largest drops from 5.5 mm diameter on, the deformations increase till the drop breaks asunder (Lenard, Meteorol. Zeitschr., June, 1904, p.256. Also Wiesner, "Beiträge zur Kenntnis des tropischen Regens," Wien. Ber. CIV, 1895). On the other hand, drops up to 4 mm diameter (even when falling in an air current blowing obliquely upward with a velocity of 10 m/sec.) could not be sundered.

In addition to these deformations, there occur ellipsoidal oscillations in freely falling drops. These were likewise investigated by Lenard and their surface tension determined therefrom (Lenard, "Schwingungen fallender Tropfen," Wied. Ann. 1887, p. 209). For the purpose of observing drops of about 1 mg weight falling successively out of a vertical tube, Lenard employed a stroboscopic method with electric sparks, which served as current breakers. He gives very interesting photographs of drop formation, the production of "ligaments" and the course of the oscillations. It has been experimentally demonstrated that when the oscillation period

$$T = \sqrt{\frac{3}{8} \pi \frac{p}{g a}}$$

remains unchanged, while the capillarity a is changed by heat or electricity, the weights p of the drops change proportionally with a .

A supplement to the researches of Lenard is given by Schmidt (Wien. Sitzungsbericht, 118, IIa and Meteorol. Zeitschrift, 1909, p.183), who determined the falling velocity of rain-drops having diameters of 3.5 down to 0.4 mm. Since we have employed in our experiments apparatus similar to that of Schmidt, we will here give a brief description of the latter. Two sheet-zinc disks were centrally mounted 20 cm apart on a vertical rod. A sector was cut out of the upper and larger of the horizontal disks. A sheet of filter paper for catching the rain-drops was stretched over the lower disk. The apparatus was set in rotation and then exposed to the rain. Only those drops can reach the lower disk which have passed through the slot in the upper disk. During the time required for the drops to fall the distance between the disks, the disks continue to turn, so that a drop does not fall on a spot directly under the slot, but always a greater or less angular distance behind, according to the velocity of the fall. The size of a drop is determined as follows: The filter paper is sprinkled with a powdered dye, which is soluble in water (eosin, e.g.) and which can be applied either before or immediately after the catching of the drops. After the process of absorption is complete, the excess of powder is shaken off. There then remain on the paper accurate pictures of the drops, which can be measured at leisure and which can serve to determine the weight of the drops, when the paper has been calibrated. According to the thickness and quality of the paper, drops are clearly

visible on it down to a diameter of 0.25 mm. Every drop which falls on the paper during an experiment, thus records its weight by the size of the spot it makes and its falling velocity by the position of the spot. Schmidt's results agree very well with Lenard's for the large drops, but he reports a smaller falling velocity for the small drops and gives for the latter a modification of Stokes' formula.

While the foregoing experiments had to do with relatively large drops, in comparison with the ones obtained in fuel spraying, we will now describe briefly a few measurements of very small magnitudes. The methods heretofore employed for measuring exceedingly small particles are utilized with the aid of the ultramicroscope. The latter is based on the well-known phenomenon which occurs when a sunbeam falls through a crack into a darkened room and lightens up the particles of dust suspended in the air, so that they become clearly visible. A description of the method of making ultramicroscopic observations and of the requisite apparatus is given by Broglie in a report, which treats of the investigation of solid particles suspended in gases.* The particles observed in the ultramicroscope find themselves, first, in the field of gravity. They move therefore in accordance with Stokes' formula. If an electrostatic field is created between two opposite metal plates, the particles find themselves, secondly, in an electric field. The motion of the particles,

* Maurice de Broglie, "Untersuchung über die gasförmigen Suspensionen," Physikalische Zeitschrift, 1910, p.33.

which can carry an electric charge e , is caused, in a field H , by a force of the intensity $H e$, while the resistance of the surrounding medium is given by the formula of Stokes, which is therefore

$$H e + m g = 6 \pi [\eta] r c *$$

The electric field can be so located that gravity and the electric force mutually offset each other. Thirdly, the particles can be moved by the pressure of light.** Fourthly, and lastly, the particles are subjected to continual impacts by the molecules of the surrounding gas. If the particles are so small that they cannot fully withstand these impacts, they acquire an unceasing restless motion, which is designated as the "Brown motion."

The size of the particles can be determined as follows: First, with the ocular micrometer, so long as their size does not too nearly approach the value of the length of light waves. Secondly, by means of Stokes' formula, as long as the particles are not so large as to have a measurable velocity in the gravity or electric field.*** Thirdly, it is possible to determine the size of particles which are so small that a Brown motion can be observed, with the aid of a photographic record of their displace-

* See also Ehrenhaft, "Methoden zur Bestimmung des elektrischen Elementarquantums," Physikalische Zeitschrift, 1909, p.309.

** Ehrenhaft, "Grossenbestimmung von Einzelpartikeln," Phys. Zeitschrift, 1914, p.952.

*** Stokes' formula loses its applicability in the electric field, when the size of the particles too closely approaches the size of the molecules.

ment and a formula developed by Einstein.*

The ultramicroscope enables us to determine the size of particles having a diameter of from about 0.02 mm down to less than 0.00003 mm.**

It was determined, e.g., that particles of cigarette smoke have a diameter of from about 0.00006 to 0.0006 mm. Further details concerning the ultramicroscopic method of experimentation and its application to the investigation of extremely small particles, especially in the electric field, can be found in the works of Ehrenhaft, Millikan, Przibram and others.***

In order to produce spherical particles of the smallest possible size for the purpose of studying their behavior in gases by means of the ultramicroscope, the method of atomization was employed which was first used in a quantitative investigation of the Brown motion by J. Y. Lee in the Ryerson Laboratory.**** Solid particles (The noble metals are especially suitable for ultramicroscopic investigations.) are obtained by the evaporation or atomization of metals by means of an electric arc light.*****

* For other methods of determining the size of the particles, see Ehrenhaft, "Ueber die Teilbarkeit der Elektrizität," Ann. der Physik, 1918, p.70, and "Die Photophoresc," Ann. der Physik, 1918, p.81.

** Ehrenhaft, "Ueber kleinste Quecksilberkügelchen," Physikalische Zeitschrift, 1915, p.230.

*** Ehrenhaft, "Electrische Ladung von Einzelteilchen," Phys. Zeitschr., 1910, p.240. Millikan, "Ladung eines Ions und Stokessches Gesetz," Phys. Zeitschrift, 1910, p.1097. Przibram, "Ueber die Ladungen im Phosphornebel," Phys. Zeitschrift, 1910, p.630.

**** Ehrenhaft, "Ueber die Teilbarkeit der Elektrizität," Ann. der Physik, 1918, p.23; "Ueber die Unveränderlichkeit der Massen kleiner Quecksilberkügelchen bei intensiver Bestrahlung," Phys. Zeitschr., 1914, p.955; "Ueber kleinste Quecksilberkügelchen," Physikalische Zeitschrift, 1915, p.227.

***** Mecke, "Ueber Kranzerscheinungen in homogenen Nebeln," Ann. d. Phys. 61, 1920, p.498.

In the experiments here referred to, their diameters ranged from 0.0001 to 0.001 mm.* For the production of liquid particles of the desired fineness, it is generally only necessary to use an ordinary glass atomizer with a blower, whose air jet is directed in the plane of the surface of the liquid, so that liquid particles are carried along by the air jet and atomized into a cloud of fine drops. Millikan describes such an atomizer in his treatise "Ueber die Ladung eines Ions und das Stokessche Gesetz" and with it obtains oil drops having diameters of 0.013 down to 0.0006 mm (Ehrenhaft, "Ladung eines Elektrons," Phys. Zeitschrift, 1910, p.620). The smallest mercury drops obtained with the atomizer had a diameter of about 0.00008 mm (Ehrenhaft, "Eine Methode zur Bestimmung des elektrischen Elementarquantums," Phys. Zeitsch. 1909, p.308).

In the investigation of fuel atomization, the ultramicroscopic method can be employed only for measuring isolated drops having a diameter of less than 0.02 mm. Often the small particles under investigation are present in very large numbers. In this event we can, under certain conditions, determine their size by an optical method. A glass plate, strewn with lycopodium, is brought between the eye and a point of light, or the lycopodium is simply blown into the air in front of the source of light, when the latter, due to diffraction is surrounded by an aureole with a colored border or with several colored rings, whose size

* Millikan, "The Isolation of an Ion," Physical Review, 32, 1911, p.351.

enables us to compute the mean diameter of the spores as about 0.03 mm.* If, therefore, the particles are suspended in such large numbers and so close together in a fluid medium as to form a cloud and if this cloud is pierced by a beam of light, then diffraction rings may be formed, from which the diameter of the particles can be calculated. Fraunhofer has already found:

1. That the intensity of the phenomenon increases with the number of the diffracting particles;

2. That the size of the colored rings is inversely proportional to the diameter of the particles;

3. That the particles must all be of the same or nearly the same size. Inequalities of the particles produce a more disturbing effect on the phenomenon, the greater and more varied the inequalities are.

Lastly, the particles must not exceed a certain magnitude, since otherwise the diffraction rings come so near the source of light that the latter, especially when somewhat extended, completely overpowers the rings and renders them invisible.

If homogeneous parallel light waves strike vertically on a diffraction grating, which consists of parallel equidistant slots, and if

l = the distance between two successive slots of the grating,

* Millikan, "The Isolation of an Ion, a Precision Measurement of its Charge and the Correction of Stokes' Law," Physical Review 32, 1911, p.351 (Smallest oil drops, radius $r = 3.13 \times 10^{-5}$ cm; largest oil drops, radius $r = 65.8 \times 10^{-5}$ cm); Millikan, "Die Existenz eines Subelektrons," Ann. d. Physik, 1916, p.759.

λ = the wave-length of the homogeneous light,

γ_m = the diffraction angle, i.e., the angle included between the direction of the diffracted rays at the point of maximum luminosity of the m-th slot-picture and the line perpendicular to the slot,

m = ordinal number of the slot-picture, then the diffraction rings are given by the expression

$$\sin \gamma_m = m \frac{\lambda}{l}$$

According to the Fraunhof-Babinet principle, the edges by which the light is diffracted, can as well be inclined toward one another as from one another, i.e., narrow rods or prisms produce the same phenomenon as slots of uniform width, and round objects the same phenomenon as round openings of the same diameter. Hence, water drops or ice crystals in the clouds can produce diffraction phenomena, which are known as aureoles, halos and coronas around the sun and moon. In order to determine the size of these drops or crystals, meteorologists measure, with reference to the eye, the angular distance between the middle of the diffraction phenomenon and the outer edge of the red ring which surrounds the aureole. Instead of this border, a dark ring is obtained with monochromatic light, whose wave-lengths correspond to a mean wave-length of white light. Thus the diffraction angle for a minimum luminosity of the white light is measured; since it is too difficult to locate accurately the brightest point in the light ring to make the angular measure-

ment accurate enough. Hence, if

φ = the angle for the outer edge of the red ring,

n = ordinal number of the red ring,

λ_m = the mean wave-length of white light = 0.0000571 cm,

b = the mean width of the ice prisms,

d = the diameter of the drops,

then we have, for the ice crystals, $b = n \frac{\lambda_m}{\sin \varphi}$

and for the water drops, $d = (n + 0.22) \frac{\lambda_m}{\sin \varphi}$

(Carl Exner's approximation formula).*

The evaluation of a very large number of observations** by means of these formulas shows that the mean diameter of cloud drops ranges from 0.01 to 0.06 mm. If the drops are still smaller, then the central field of the aureole, which should be nearly white with white light, becomes vividly colored, until finally, as soon as the drops get smaller than the wave-length of light, the diffraction phenomena disappear, since it can occur only so long as $\sin \varphi < 1$ and $d > \lambda$. If the diameter of the drops approaches the wave-length of light, the so-called Tyndall phenomena***, a blue coloration of the cloud, may occur

* Pernter, "Meteorologische Optik, 1910, p.430; Reinhard Mecke, "Experimentelle und theoretische Untersuchungen über Kranzerscheinungen im homogenen Nebel," Ann. d. Phys. 1920, pp. 471 and 623. According to the latter, the formula is valid only for drops of over 0.008 mm diameter.

** Measurements of Kämtz and on Ben Nevis reported by Pernter, Meteorologische Optik, 1910, p.466. See also Hilding Köhler, "Ueber die Tropfchengrößen der Wolken und die Kondensation," Meteorologische Zeitschrift, 1921, p.359.

*** Phil. Mag. 1869, p.334. Freundlich, "Kapillarchemie," p.297. Bock, "Der blaue Dampfstrahl," Ann. d. Phys. 1899, p.674.

on the illumination of a cloud consisting of such small drops. Phenomena of this nature can hardly be observed in fuel atomization, even under the maximum atomization pressure.

If, on the contrary, the diameter of the drops increases to over 0.06 mm, then the accuracy of the determination of the diffraction angle rapidly diminishes, since, on the one hand, the effect of the experimental error on the result constantly increases as the angle decreases and, on the other hand, the red rings become continually fainter as the size of the drops increases. If the drops are of various sizes, then the red border of the aureole vanishes and there remains only a bright halo around the source of light.

In a manner similar to that of the meteorologists, Stodola* also utilized the diffraction phenomena for determining the size of the condensation drops, which are produced in a bottle partially filled with water, from which the air is suddenly partially exhausted by a jet air-pump. Behind the bottle, on which fell the parallel light rays from an electric arc light, there was a system of lenses with a focal length f and a screen at the distance f behind the lens. After the light had been diffracted by the condensation drops, each set of parallel diffracted rays was converged by the lens system to a point on the screen.

There was thus produced on the screen a corona of concentric colored rings, or, in the case of homogeneous light, a corre-

* Stodola, "Die Unterkühlung beim Ausfluss gesättigten Dampfes mit Rücksicht auf die Molekularvorgänge," Z.d.V.d.I., 1913, p.1780.

sponding corona of concentric light and dark lines, whose radius R could be measured on the screen. The diffraction angle ϕ could then be computed from

$$\tan \phi = R/f \sim \sin \phi$$

Stodola measured the radii of the bright rings, for which, in the case of spherical drops with the radius r , he employed the following formula

$$\sin \phi = \frac{m}{\pi} \frac{\lambda}{r}$$

in which $m/\pi = 0.819$ for the innermost bright ring; 1.346 for the second ring; 1.858 for the third ring.* The diameter of the condensation drops was found to range from 0.0016 to 0.0048 mm.

If the investigation of the diffraction phenomena is undertaken in the laboratory with an artificial source of light (point or line of light), whose distance from the diffracting particle is known, then we can either measure the radius of the aureole or color-ring directly by means of a scale applied to the source of light, or we can adjust the aureole to a given size by shifting the source of light and the scale (or an illuminated slot in a screen), which has small holes at given intervals to mark the distances from the slot.

If R is the radius of an aureole or of a color-ring CC' , which surrounds the source of light or the light-slot A , and if A (along with the scale) is at a distance L from the

* Pernter, Meteorologische Optik, p.442.

light-diffracting particles at B, we then have, for parallel rays of light

$$\sin \gamma = \frac{R}{CB} \quad \text{whereby} \quad CB = \frac{L}{\cos \gamma}$$

$$\sin \gamma = \frac{R \cos \gamma}{L}$$

For the first maximum brightness with homogeneous light of wave-length λ and for the grating constant l , we then have

$$l = \frac{\lambda}{\sin \gamma} = \frac{\lambda L}{R \cos \gamma}$$

Since $\cos \gamma$ is almost equal to one and l , in the first approximation, is equal to the diameter of the drop, we have, for the latter,

$$d = \frac{\lambda L}{R}$$

In this manner, by employing an incandescent light with a single carbon filament as the line of light, Quincke found the mean diameter of particles of silicic acid, floating in a solution of water glass, to be from 0.008 mm to 0.011 mm (Quincke, "Ueber unsichtbare Flüssigkeitsschichten" etc., Ann. d. Phys. 1902, p.672. Bock found the size of water drops, produced by condensation in a jet of steam blown into the free air, to be from 0.0034 to 0.0046 mm in diameter. He employed, as a pointed source of light, the glowing magnesium pencil of a Linnemann burner. (Bock, "Der blaue Dampfstrahl," Ann. d. Phys., 1899, p.683.)

In the previously-mentioned experiments, the drops were produced in a manner having little or nothing in common with fuel atomization. These experiments were mentioned, however, because they show us where to find practical methods for our researches and because no quantitative investigation had previously been made of the drops produced in the atomization of fuels, there being only a few estimations available.

In an investigation of the process in a carburetor spray by Heuser ("Untersuchungen des Vorganges im Spritzvergaser," Dissertation, Dresden, 1920) the carburetor vapors of heavy benzine, water and benzol were observed in the Pallas and Zenith carburetors. At low velocities the drops measured up to 0.2 mm, while at high velocities they appeared to be hardly smaller than 0.01 to 0.005 mm in diameter.* In an article by Chaloner on fuel injection, it is stated that, with compressed-air injection, the drops have a diameter of at least 0.38 to 0.51 mm. No information was given as to how these values were obtained.**

We also refer you to a report by Dr. Siegens on the Krause method.*** The Krause apparatus is an air drier and consists of a rotating vaporizer disk with a peripheral velocity of about 160 m/s. The solutions to be dried are applied to the surface of the disk, from which they are finely atomized in an airstream

* Heuser's dissertation did not state how the drops were measured. Apparently it was only by visual estimation.

** J. L. Chaloner, "Air Injection or Mechanical Injection," Motorship, New York, 1921, p.133.

*** Dr. Siegens, "Ueber das Krauseverfahren," Zeitschrift für angewandte Chemie, 1922, p.533.

at about 150°C. Microscopic measurements of the size of the particles of powder obtained from solutions of known concentration demonstrated that the atomization in the Krause apparatus produced drops of 0.005 to 0.03 mm in diameter.

Choice of Experimental Method.

The practical reasons for studying fuel atomization, are to explain and improve the processes which take place in internal combustion engines. It appears therefore very desirable to institute the experiments from the start on a basis corresponding as closely as possible to the actual running conditions of an engine. The employment of the fuel nozzle of an engine which has already served successfully and the investigation of customary fuels seem therefore to be advisable. The difficulty of the problem, however, necessitates slow progress. Since, hitherto, neither quantitative experiments have been made nor any theory of atomization has been established, we must first find the bases for further complicated researches. Hence we must begin our researches under the simplest possible conditions, i.e., we must eliminate a number of factors which are difficult to determine and which occur in actual operation. Hereby we abandon the conditions of actual operation, but this is necessary, in order to penetrate the problem at all. The most decided simplification consists in injecting the spray into the free air under normal atmospheric tension and temperature, instead of into

a closed chamber filled with highly compressed and heated air, for the sake of enabling direct observation and experimentation without aggravating complications. It then seems necessary to investigate the properties of the atomizing spray at first with relation to only a few quantities, especially the atomization pressure. Only one quantity can be changed in each series of experiments and hence it must be endeavored to keep all the remaining variable elements as constant as possible or else to eliminate them, while as permanent a condition as possible of the atomization jet must be maintained in the individual experiments by keeping all the factors as constant as possible. Consequently, it is not advisable to imitate the jerky motions of the fuel valve which would vary the vaporization pressure, but it is better to undertake the individual experiments in a continuous jet at a constant atomization pressure. Finally, we wish to limit our experimental program to the testing of a nozzle with "solid injection." "Air injection" is still a very complex process, in which there is no continuous fuel jet and which would require a considerably more comprehensive experimental outfit.

The experiments referred to in the preceding paragraphs, as also the attentive observation of the atomization jet, lead to the conclusion that, in solid injection, the diameter of the drops is not greater than 0.2-0.5 mm and probably not smaller than 0.01-0.001 mm. The smaller drops lie in a region, for the investigation of which the optical method of light diffraction

seems admirably suited. The advantages of the optical method are obvious. We can, at any instant, determine the size of the drops from the size of the aureole and we can therefore study the effect of rapidly changing causes on the atomization. We can illuminate the whole jet and investigate its various parts. The size of the aureole (with a constant distance of the source of light) depends entirely on the size of the drops, so that the experiments give direct and reliable results, which cannot be impaired by uncontrollable secondary influences. The illumination seemed to be an ideal method for investigating the atomization jet, which formed (especially at high pressures) a dense cloud, and was therefore tried first of all.

At a distance of about 5 meters from the atomization jet there was placed a Nernst lamp (from which the heating spiral had been removed) as the line of light, or there was placed in front of the source of light a screen, with a slot which served as the luminous line, and the conical jet was optically investigated at various pressures throughout its whole extent, from the nozzle to a distance of about one meter, with white and with monochromatic light. Thereby unmistakable diffraction phenomena arose, since the characteristic white or (with homogeneous light) bright nucleus of an aureole was observed. This brightening of the central field was most intensive, when one looked through the portion of the jet nearest the nozzle and very rapidly vanished with increasing distance from the nozzle, corresponding to the greater

distance between the drops in the conically spreading jet. There was nowhere any margin to the aureole to be observed, let alone any indication of a color band. This can be taken as a sure proof that the individual drops in the jet differ so greatly in size that the diffraction phenomena, observable in the circle around the source of light, overlap one another with increasing irregularity and mutually obliterate one another. Even with illumination of the fine cloud, which constantly increases at higher vaporization pressures and is evident even near the nozzle, only a brightening could be observed around the source of light, but no color phenomena. It is perhaps possible, at very high pressures in Diesel engines with solid injection above 600 atmospheres, for the atomization to be so uniform that measurable diffraction phenomena can be produced. It is highly probable, however, that such is not the case and that, presumably, successful results, even with the highest pressures, can be obtained by the optical method, only when we succeed in separating the drops (ever growing smaller at the high pressures, due to their rapidly decreasing velocity) according to their size, by a suitable process, to such an extent as to form cloud layers of drops, whose size is sufficiently uniform to produce a measurable aureole. At the relatively low pressures attainable with the means at our disposal, experiments in this direction gave no promise of success and consequently the optical method had to be abandoned.

The fact that the drops in one and the same jet varied ex-

ceedingly in size was immediately confirmed by catching portions of the spray on blotting paper. A comparison of the oil spots made by neighboring drops showed that they often differed manyfold from one another. Hence it is useless to try to determine the size of individual drops, since this would entail an almost infinite number of measurements, in order to obtain the correct average value. Some method must, moreover, be found, for the simultaneous measurement of as many drops as possible. The best method seems to be the observation of the mean falling speed of a cloud of drops. Even this method, however, can have any chance of success only at very high pressures, since, so long as the drops in the center of the cone are still so large, that their high initial velocity is only very gradually reduced by friction with the air, it is impossible to find or produce a definite level for a cloud of drops, the sinking of which can be observed.

There remains no other way than to catch the largest possible number of drops in some suitable manner for finding their average size. The method of measuring the size of the oil spots formed by the drops can hardly be employed, since this would entail innumerable measurements. Moreover, the drops would have to be caught on calibrated paper and, since the small oil spots would not show clearly enough on the paper, they would have to be rendered visible by a chemical method, which would be difficult, in view of the fact that liquid fuels are nearly all neutral. We have seen, e.g., that the method with eosin powder

can be used only for drops having a diameter of not less than 0.25 mm. The size of the drops can therefore be determined only by weighing, their number and nearness being limited only by the ability to count them.

It was therefore decided to separate (from the atomization jet by means of a shutter) the largest practicable number of drops, to catch them on a suitable pad, to weigh and count them and therefrom determine the average size of the drops for the measured atomization pressure. This method was employed to its uttermost limits and only for still greater atomization pressures did other new methods have to be found. At an atomization pressure of 42 atmospheres, the corrected total weight of 12000 drops, which were collected on a smoked glass plate (experiment No. 342), was, e.g., only 0.47 mg. The glass plate weighed 26540 mg. The layer of soot weighed 9-10 mg and underwent, by absorption of atmospheric moisture and its evaporation, during the experiment and subsequent weighing in the balance chamber, changes in weight which could vary between 0.15 and 0.30 mg. The time during which the smoked glass was exposed to the atomization jet was about 0.0005 second. The average diameter of the drops was computed to be 0.045 mm. It seems hardly practicable to have a smaller total weight of the drops, without rendering the correctness of the results too uncertain, while it is hardly possible, on the other hand, to count accurately a larger number of drops, since the spots made by the smallest

ones on the soot are already hardly visible to the naked eye.

Translation by Dwight M. Miner,
National Advisory Committee
for Aeronautics.

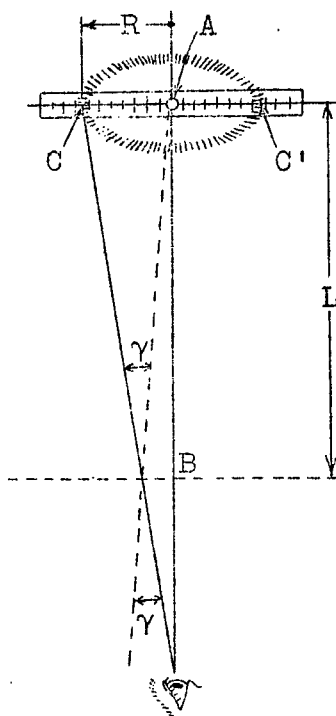


Fig.1

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